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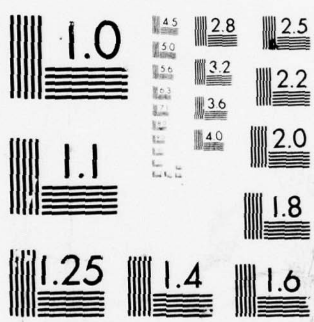

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APPLICATION OF LIGHT EXTINCTION MEASUREMENTS TO THE STUDY OF COMBUSTION IN SOLID FUEL RAMJETS.

by

(10) Michael Edward Hewett

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Thesis Advisor: D.W. Netzer

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(20. ABSTRACT Continued)

Utility and limitations of the optical method are presented.

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Application of Light Extinction Measurements to the Study of Combustion in Solid Fuel Ramjets

by

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Lieutenant, United States Navy
B.S., University of Washington, 1969

Submitted in partial fulfillment of the requirements for the degree of

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from the

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Richard W. Bell, Chairman, Department of Aeronautics

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ABSTRACT

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LIST OF FIGURES

NOMENCLATURE

A/F_T	-	Air to fuel ratio total
A/F_G	-	Air to fuel ratio through grain only
C_{m_F}	-	Mass concentration front, gm/cm^3-gal
C_{m_B}	-	Mass concentration back, gm/cm^3-gal
D_{32}	-	Average particle diameter, μm
G	-	air flux, $lbm/sec\text{-}in^2$
L	-	the length the light beam travels through the aerosol
P_c	-	Pressure in combustion chamber, psia
$\dot{r}$	-	regression rate of fuel, in/sec
T_F	-	transmissivity front
T_B	-	transmissivity back
η	-	temperature rise efficiency
ρ	-	carbon particle density, gm/cm^3
$\dot{\omega}_P$	-	primary mass flow, lbm/sec
$\dot{\omega}_S$	-	secondary mass flow (bypass), lbm/sec
% Front	-	Percent of unburned carbon front
% Back	-	Percent of unburned carbon aft

ACKNOWLEDGEMENTS

The author wishes to express his appreciation to Associate Professor David W. Netzer of the Department of Aeronautics for his guidance and assistance throughout the project.

A special note of appreciation also goes to Frank Abbe and Ted Dunton for their timely and dedicated technical assistance.

I. INTRODUCTION

A better understanding of the internal ballistics of the solid fuel ramjet continues to be a necessary goal, if the concept is to become a viable tactical propulsive system.

Past studies have shown the importance of parameters such as flame holder step size, aft combustor entrance step size, aft mixing chamber L/D and aft mixing techniques.

Recent work done by Mady and Netzer [Ref. 1], to better understand the effects of bypass air on combustion efficiency, was conducted by varying bypass mass flow rates, dump momentum, number of dumps and angular orientation into the aft mixing chamber.

High regression rates were reported for PMM fuel grains when bypass air was injected into the aft combustor The regression rate for bypass configurations took the form:

$$\dot{r} = 0.0016\, P^{.42}\, G^{.003} \qquad (1)$$

It was suggested that in the bypass configuration (low G, high P and fuel rich) the principal mechanism for wall heat flux became radiation and thus made the regression rate insensitive to G.

For the non-bypass configuration for PMM fuel grains, regression rates took the form:

$$\dot{r} = 0.0043\ P^{.29}\ G^{.38} \qquad (2)$$

Performance computations showed a significant decrease in combustion efficiency for all bypass configurations which were used.

Work at the Naval Weapons Center, China Lake, and at Chemical Systems Division, United Aircraft, have shown that when all-hydrocarbon fuel grains were used in the solid fuel ramjet combustion efficiency could be improved with proper introduction of bypass air. Much of the PMM fuel probably becomes a monomer in the gaseous phase, while all-hydrocarbon fuels probably leave the fuel surface as larger polymers. This was suggested as the most significant reason for the variation in bypass performance with fuel selection.

Additional experimental work by Schadow [Ref. 14] with all-hydrocarbon fuels, and modeling efforts by Netzer [Ref. 15], have indicated that a considerable amount of unburned carbon may be present. It has also been suggested that inefficiency of the combustion process is directly related to the unburned carbon. Modeling efforts at CSD [Ref. 16] have also assumed that approximately 50% of the vaporized fuel escapes from under the flame within the fuel grain and

enters the exhaust mixing chamber. The above conclusions were based on indirect data (such as combustion efficiency, fuel regression rate, etc.) except for the gas sampling and temperature measurements made by Schadow. Direct evidence of the effects of bypass on combustion behavior remains to be obtained.

In recent years considerable advances have been made in the utilization of light extinction and light scattering methods [Ref. 5 and 6] for the study of combustion behavior. Lee, Singer and Cashdollar [Ref. 2] have employed an optical transmissometer for measuring carbon particle size and concentration in a wood tunnel fire. Lester and Wittig [Ref. 4] successfully utilized the light extinction method to find particle sizes and concentration during methane combustion in a shock tube. Zinn, Powell and Cassanova [Ref. 3] utilized both the extinction and forward scattering of light measurement methods to study smoke particles in building fires. Although the latter method negates the requirement for a priori knowledge of the refractive index of the particles, it is more difficult to adapt to practical combustion chamber geometries. Bernard and Penner [Ref. 7] have also used scattered laser power spectra to determine particle sizes in flames.

This research was concerned with further investigation of the combustion process within solid fuel ramjets. The combustion process was studied by monitoring the unburned

carbon particle size and concentration in the aft mixing chamber, both at the fuel grain exit and just prior to the exhaust nozzle. An optical technique was employed which involved the light extinction method of measuring average particle diameters in an aerosol [Ref. 5 and 6].

II. METHOD OF INVESTIGATION

Experimental firings of a solid fuel ramjet were conducted using both polymethylmethacrylate and all-hydrocarbon fuel grains. The tests were performed to further investigate the effects of bypass airflow by varying primary to-bypass air flow ratios.

An in situ optical technique was utilized to measure average size and concentration of carbon particulates generated during the combustion process. The method involved continuous measurement of light transmission at two positions in the aft mixing chamber (Figure (1)).

The extinction measurements record the total amount of light removed from a beam passing through the combustion chamber as a result of Mie scattering and absorption by carbon particles present in the aerosol. The transmission of light through an aerosol of particles is given by Bouguer's Law [Ref. 8]:

$$T = e^{-\gamma L} \qquad (3)$$

The intensity of the light beam decreases exponentially with distance (L) as it penetrates the aerosol, with a rate of decay regulated by the turbidity γ. The turbidity for the case of a polydispersed size distribution is given in Reference 2:

$$\gamma = \frac{3}{2} \frac{\bar{Q}\, C_m}{D_{32}\, \rho} \tag{4}$$

where C_m is the mass concentration of particles, ρ is the density of an individual particle, D_{32} is the volume to surface mean diameter, and $\bar{Q}$ is the average extinction coefficient. The extinction coefficient $\bar{Q}$ is calculated as a function of particle size distribution, wave length of the light beam and the complex refractive index of the particle using Mie scattering theory. Using a log normal particle size distribution with a standard deviation of $\sigma = 1.5$ and a refractive index for carbon of 1.95 - .66i [Ref. 12], Mie extinction coefficients for three wave lengths, 4579A, 5145A, 6328A, are shown in Figure 2.

Average extinction coefficient curves for a mono-dispersed size distribution are also shown in Figure 3. These plots were provided by K.L. Cashdollar of the Pittsburgh Mining and Safety Research Center, Bureau of Mines.

From Bouguer's Law [Ref. 2] the ratio of the logarithms of the measured transmissions at any two wave lengths is equal to the ratio of the computed average extinction coefficients.

$$\frac{\log T_{\lambda_1}}{\log T_{\lambda_2}} = \frac{\bar{Q}_{\lambda_1}}{\bar{Q}_{\lambda_2}} \tag{5}$$

Curves from which average particle size can be found as a function of the $\overline{Q}$ ratios are shown in Figures 4 and 5.

As noted by Cashdollar in Reference (2), use of three wave lengths provides a redundancy over most of the particle size range. If the three measured log transmission ratios do not yield the same approximate average particle diameter, then the particle size distribution and/or the refractive index may not be correct.

Once the mean particle size and extinction coefficient have been determined, the mass concentration can then be computed from:

$$C_m = -\frac{2}{3} \frac{\rho D_{32}}{\overline{Q}_\lambda L} \ln T_\lambda \qquad (6)$$

As previously mentioned, the use of extinction methods assumes that an accurate knowledge of the refractive index is available.

There exists an uncertainty as to the refractive index of carbon soot. Reference (4) suggests the possibility that the refractive index may vary with the H/C ratio. Senfleben and Benedict [Ref. 12] have determined refractive index values of 1.95-0.66i and 1.75 - 0.74i respectively. Cashdollar originally chose to use 1.57- 0.56i from Dalzell's work [Ref. 9], but later lowered the imaginary part to 0.33i in order to obtain better agreement between three wave lengths [Ref. 17].

Average particle diameters computed for this experiment were based on a refractive index of 1.95 - 0.66i because of the availability of extinction coefficient curves computed at this refractive index.

Cashdollar chose to use light wave lengths of 4500, 6328 and 10,000 angstroms. However, in applying the technique to flame measurements, considerable light emission in the infrared region of 10,000 angstroms makes this frequency unusable. For the solid fuel ramjet combustion studied in this investigation 5145A was used rather than 10,000A. However, it offers less in the way of redundancy to the measurement, as it is closer to the other frequencies than desired. For the purpose of particle diameter determination computed from the extinction coefficient ratio, $\bar{Q}_{6328}/\bar{Q}_{4500}$ was considered most accurate because of the larger spread between the wave lengths [Ref. 6, pg. 1353].

The extinction coefficient curves used were computed for both a log normal particle size distribution with a standard deviation $\sigma = 1.5$ and a monodispersed distribution. Wersborg [Ref. 10] indicates that for small soot particles in flames a narrow size distribution has been observed to be a Gaussian distribution. However, he also reports a change to a log normal distribution in the tail of a flame.

Lester and Wittig [4] conclude from Wersborg's results that for the study of nucleation and surface growth in a combustion environment, the monodisperse approximation is reasonable for the calculation of size and concentration.

Average diameters D_{32} were computed in this experiment from log normal and monodispersed distributions, the latter giving better results in the majority of instances.

It is felt that the particle size and concentration measurements would be within 10-15% accuracy. In addition to the reasonably good quantitative results, relative changes in these parameters during various burning configurations and time frames provide a valuable tool for analysis of the combustion process.

III. DESCRIPTION OF APPARATUS

A. RAMJET MOTOR

The stainless steel solid fuel ramjet motor was that previously used by Mady [Ref. 1]. The only modifications made to the motor were the installation of an improved ethylene-oxygen igniter system in the head-end assembly and the machining of two 9/16 inch diameter ports in the aft mixing chamber. The ports allowed an external light source to penetrate through the aft mixing chamber at two axial locations (Fig. 6). Fuel grains used were polymethylmethacrylate and an all-hydrocarbon fuel supplied by the Naval Weapons Center, China Lake.

Combustion chamber and inlet pressures were measured with a Wianko 0-150 psig pressure transducer. When bypass air was utilized, two 0.813 in. diameter dump ports were located 180° apart and just aft of the mixing chamber recirculation zone.

The inlet diameter was 0.50 inches in diameter and the fuel grain internal diameters for the PMM and all hydrocarbon fuel were 1.50 and 1.30 inches, respectively.

The exhaust nozzles used were converging nozzles with a 0.746 inch throat diameter for the PMM firings and a 1.0 inch throat diameter for the all-hydrocarbon fuel tests.

To extinguish the flame at the end of a firing, air flow was terminated and nitrogen was momentarily fed into the system from high pressure bottles at 80 psig.

B. AIR FLOW CONTROL

The air flow control consisted of manually operated valves. Flow measurements were made with ASME orifices.

C. TRANSMISSOMETER APPARATUS

The light source used was a SLM-1200 slide projector which housed a 1200 watt tungsten-halogen lamp (Sylvania BRN-1200). The light was focused through the projector lens system onto a pin hole on one end of a 3" x 5" x 10" blackened aluminum box (Fig. (6)). The pin hole produced a nearly point source illumination and was used with a collimating lens in the box to produce a collimated light beam. The collimated light beam was then directed through a 9/16" diameter hole on the opposite end of the collimator box.

The beam was then split with a 50/50 plate beam splitter. The first beam was directed (through a 0.46" ID steel tube) to the front portion of the mixing chamber. The second beam was appropriately deflected and directed to the aft end of the mixing chamber just prior to the exit nozzle. After both beams penetrated the chamber cavity they were again directed through 0.46" I.D. tubing to two individual light detector units.

The light directing tubes were sealed using synthetic sapphire windows mounted in an O-ring sealed coupling. The coupling was designed for quick removal of the windows for cleaning between engine firings. The windows were located 10 inches from the combustion chamber.

The distance traveled by the light beam through the 9/16" O.D. (0.46" ID) tubing, prior to reaching the light detector, was nominally 24 inches. This limited the angular field of view of the detector to 1.1°. Cashdollar [Ref. 2] used 1.9° in order to eliminate any significant forward light scattering detection.

Each detector box consisted of two plate beam splitters which created three individual beams of light (Fig. 7). 2" x 2" narrow pass light filters of wave lengths 6328, 5145 and 4500 Angstroms were placed directly in front of three silicon photovoltaic detectors. The detectors provided adequate spectral response between 2000 and 11,500 Angstroms. The output of each photodetector was input to an operational amplifier, providing linearity between light intensity and voltage output. Both front and back detector systems were tested simultaneously for linearity by placing several calibrated neutral density filters in front of the collimator box output. Both systems (front and back) were linear within 3%.

D. DATA ACQUISITION

All transducer outputs for pressure measurements along with a 5 cycle per second timing signal were connected to Honeywell Model 2106 Visicorder. Photodetector output was recorded on multiple-pen, paper chart recorders (Appendix).

The connections were made such that the front and back light sources of the same wave length were plotted on the same recorder.

E. AIR FEED SYSTEM

A Pennsylvania air compressor supplied air at a pressure of 150 psia. When firing the all hydrocarbon fuel, the air from the compressor was routed through the heat exchanger of a Polytherm air heater and provided non-vitiated hot air up to 380°F.

IV. EXPERIMENTAL PROCEDURE

All test firings were performed in the jet engine test cell at the Naval Postgraduate School.

When testing PMM fuel grains, multiple firings were made at bypass ratios (primary/bypass) of 100/0, 70/30, 50/50 and 30/70, with a nominal total air mass flow rate of 0.2 lbm/sec. Reduced mass flow rates of 0.1 lbm/sec with no bypass were also tested. Bypass dump diameters of 0.813" and 0.25" were employed.

When firing the all hydrocarbon fuel, bypass ratios of 100/0 and 50/50 were attempted. Only two (2) of six firings were suitable for data reduction. Two grains burned out completely before they could be extinguished and two other grains required multiple ignition attempts.

Temperature rise efficiencies were calculated for each test. Inlet temperatures were measured and "actual" combustor total temperature was calculated using measured flow rates and combustion pressure. The NWC PEPCODE program was used to generate the theoretical combustion temperature and required gas properties (gas constant and specific heat ratio) at the experimentally determined air fuel ratio.

Weighing each fuel grain before and after a firing provided the needed data for determining the fuel regression rate and fuel mass flow rate ($\dot{m}_f$). Regression rate

calculations based on inside aft diameter variation were also included in the data reduction.

Transmissivity measurements were successful on both front and back light detector systems when firing PMM fuel at 100/0 and 70/30 bypass ratios. When operating at 50/50 or 30/70, however, the light transmission during steady state burning through the front portion of the mixing chamber was below the sensitivity of the recording system. Light transmission was always measurable in the aft end of the mixing chamber when firing PMM fuel grains.

In the case of all-hydrocarbon fuels neither front nor back detection of light transmission was possible with a 100/0 (no by-pass) configuration. During 50/50 bypass tests, low transmission levels were measurable in both front and aft positions through the mixing chamber.

V. RESULTS AND DISCUSSION

Twelve firings of PMM and six firings of the all-hydrocarbon fuel were conducted. Combustion efficiencies and regression rates were computed using the program developed in Reference 1, with appropriate modifications for the all-hydrocarbon fuel. Appendix A contains the computed performance parameters and light measurement data.

A. PMM FUEL

Test firings of PMM with no bypass (100/0) indicated that the regression rate varied within 3% (except for one test) of:

$$\dot{r} = 0.0043\ P^{.29}\ G^{.38} \tag{7}$$

as found by Mady [Ref. 1]. The results were also within 5% of Boaz's data correlation [Ref. 11]

$$\dot{r} = 0.00194\ P^{.51}\ G^{.41} \tag{8}$$

With application of bypass air to the PMM tests, the regression rates continued to follow equation (7). This was opposite to the findings of Mady whose regression rates did not vary significantly with bypass and no longer followed equation (7).

The computed combustion efficiencies for bypass and no-bypass test configurations showed (in contrast to Mady's experiments) no degradation in performance.

The contradictory results prompted an investigation of possible differences in the PMM fuel and/or in test procedures. All air mass flow measurement orifices were recalibrated and found to be accurate. Samples of PMM used in both experiments were accurately measured for possible differences in density and found equal. Information received from the PMM manufacturer (Rohm-Haas) indicated a possible difference in lots of PMM due to a curing process. It was suggested that when curing thick sections of PMM a possible variation in the amount of residual monomer in the solid may occur.

Subsequently, a sample of each lot was ignited in atmospheric air with an oxygen acetylene torch and a significant difference in the surface combustion was apparent. It can be seen in Figure 8 that the sample used in this experiment appeared to have a considerable fizz layer on the surface, indicating the probable existence of large quantities of monomers leaving in a gaseous state. The sample from Mady's experiments, although showing some surface fizz, produced large gas bubbles well below its relatively smooth combustion surface.

With the assumption that the previously employed fuel came off the surface predominantly as polymers rather than monomers, a plausible explanation for the higher regression rates in the bypass runs can be made. For a low mass flux of air through the grain, as for 50/50 bypass, a fuel rich condition occurred. A high concentration of fuel polymers

reaching the flame would lead to cracking and the production of increased quantities of free carbon. The increased presence of carbon would enhance radiative heat transfer to the fuel surface, increasing the regression rate.

With the high regression rate and resulting fuel rich situation, the temperatures in Mady's experiments must have been low enough that when bypass air was injected into the aft mixing chamber the combustion process was quenched.

In the current experiments, if monomer production predominates, the reactions would be more rapid and complete and less carbon would be produced by cracking type processes below the flame zone. Less radiative heat transfer would result, with correspondingly lower fuel regression rates. The lower regression resulted in near stoichiometric air-fuel ratios within the fuel grain with 50/50 bypass. The bypass air would then mix with the hotter combustion products which have only small quantities of unburned fuel. The subsequent reactions apparently occurred without quenching, resulting in high combustion efficiencies.

Light transmission measurements for no-bypass (high G_{air} through grain) show approximately 70% transmittance at the end of the fuel grain and approximately 75% transmittance at the entrance to the nozzle. This indicates that a considerable amount of combustion occurs prior to the gas reaching the mixing chamber. Assuming for simplicity that the gas properties and carbon concentration are uniform

at any cross section of the aft mixing chamber, the percentage of unburned carbon can be estimated. It varies linearly with concentration and gas velocity and inversely with the total carbon flow rate. This assumption is obviously weak at the aft end of the grain where reverse flow occurs in the recirculation region. For the no-bypass conditions given above this resulted in approximately 3% unburned carbon at the grain exit and 2% at the nozzle entrance. When the air flow rate was reduced (without bypass) by 50% the fuel flow rate decreased by approximately 30%. However, the air-fuel ratio remained fuel lean. The transmittance at the aft end of the fuel grain remained unchanged. For this lower air mass flux, the transmittance of 70% corresponds to approximately 4% unburned carbon. Thus a slightly higher percentage of unburned carbon was present (although less total carbon) than for the high flow rate condition. Transmittance at the nozzle entrance increased for the lower flow rate but resulted in approximately the same percent of unburned carbon.

In the 50/50 bypass configuration transmittance at the fuel grain exit was less than 5%. This is considered the minimum measurable transmittance level for the present system. This indicated that greater than 30% of the carbon produced was unburned leaving the fuel grain (or rather leaving the fuel grain and trapped in the recirculation zone). These results indicate that even with near

stoichiometric mixture ratios within the fuel port, a considerable amount of unburned carbon is produced. With the higher regression rates obtained in Mady's experiments, excessive amounts of carbon must have been produced. The transmittance measured at the nozzle entrance increased to approximately 60%, which equates to between 4 and 6 percent unburned carbon. For the combustion of PMM with air, 1% unburned carbon reduces combustion efficiency by approximately 1% (if fuel lean). The difference in efficiency between no bypass and 50/50 bypass was negligible, and this is in agreement with the 2 to 4 percent efficiency change estimated from the transmittance measurements.

The percentage of unburned carbon is determined from the computed carbon concentration, C_m, which is determined by the transmissometer readings. The particle sizes measured were in the 0.1 to 0.25 μm range. This agrees with carbon particle size measurements in flames and smoke made by other investigators. In any case, a variation in particle diameter between 0.1 and 0.3 μm does not significantly affect C_m since in this range $\overline{Q}$ varies in an approximately linear manner with particle diameter, D_{32}. This can be seen from the equation for particle mass concentration:

$$C_m = \ln T \left(- \frac{2}{3} \frac{\rho \, D_{32}}{\overline{Q} \, L}\right) .$$

One of the more interesting results of these experiments was the unexpected change in bypass performance compared to Mady's data. These differences apparently resulted from small variations in manufacturing methods. The production of monomers enhanced bypass combustion efficiency but reduced regression rate by significantly reducing the radiation produced by carbon particles.

B. ALL-HYDROCARBON FUEL

Transmissivity measurements for the all-hydrocarbon fuel firings were less than 5% at both positions in the mixing chamber, when no-bypass was employed. However, during a 50/50 bypass run a 9% transmittance was measured at the fuel grain exit and 33% transmittance at the nozzle entrance. For the all-hydrocarbon fuel this corresponded to approximately 19% and 10% unburned carbon, respectively. Both runs achieved approximately the same combustion efficiency. For this fuel, 2% unburned carbon changes temperature rise efficiency by approximately 1% (increases for fuel rich and decreases for fuel lean). Interestingly, for both fuels the percent unburned carbon measured accounts for approximately one-half of the total loss in combustion efficiency.

The question then is: why, in the 100% no-bypass run could light not be measured at the grain exit, and yet in the 50/50 test (a more fuel-rich condition at the grain exit) light was measured? Typically, a higher percentage of unburned fuel is produced in bypass tests (for examples see PMM data

in Appendix A). One plausible cause could be the effect of high air velocity (and temperature) during the non-bypass run. The polystyrene beads in the fuel could have been separating from the surface and passing into the aft mixing chamber without reacting.

The two runs conducted were not for the same total flow rate. However, the bypass did not affect the combustion efficiency. Other investigators have reported increases and decreases in combustion efficiency with varying bypass configurations and dump momentums. Too little data for the all-hydrocarbon fuel were obtained in this study to reach any new conclusions with regard to the effect of bypass on combustion efficiency.

VI. CONCLUSIONS AND RECOMMENDATIONS

1) The optical extinction measurement provides a valuable new tool for the study of combustion within the solid fuel ramjet.

2) The optical technique has some limitations, the major ones being: a) the maximum amount of carbon particles measureable is limited to the sensitivity in the low transmission levels; b) larger particles/material flowing in a system can possibly prevent any light measurements; and c) predicted particle size is somewhat sensitive to the type of particle distribution and refractive index assumed.

3) The use of laser light sources should increase the versatility of the method.

4) Carbon particle size did not vary appreciably (0.1 to 0.3 μm) with fuel type or test conditions.

5) The percent unburned fuel accounts for approximately one-half of the total loss in combustion efficiency.

6) Variations in fuel manufacturing processes apparently can significantly change the combustion behavior.

7) High air flow rate can apparently strip polystyrene beads from all-hydrocarbon fuels.

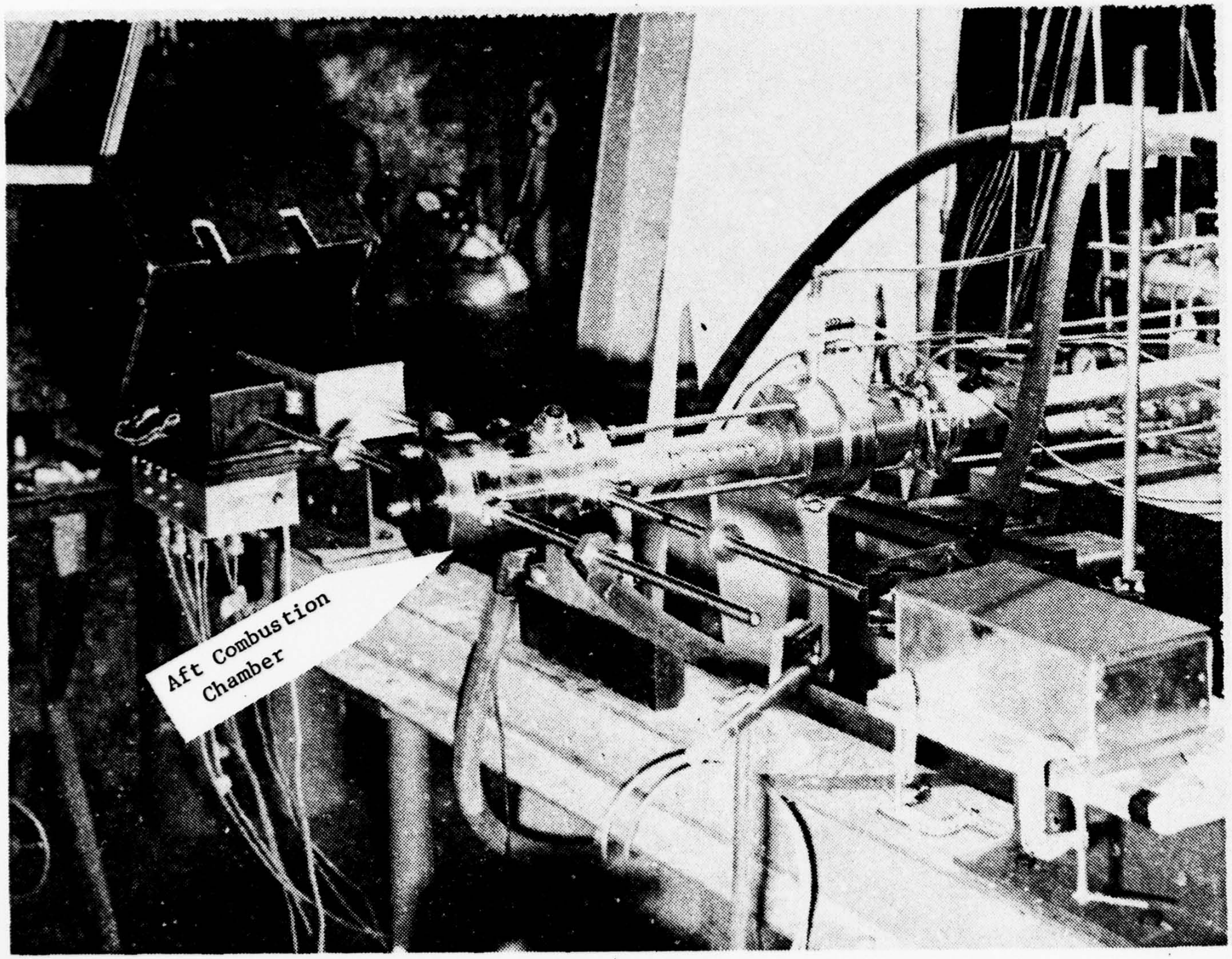

FIGURE 1. SOLID FUEL RAMJET MOTOR

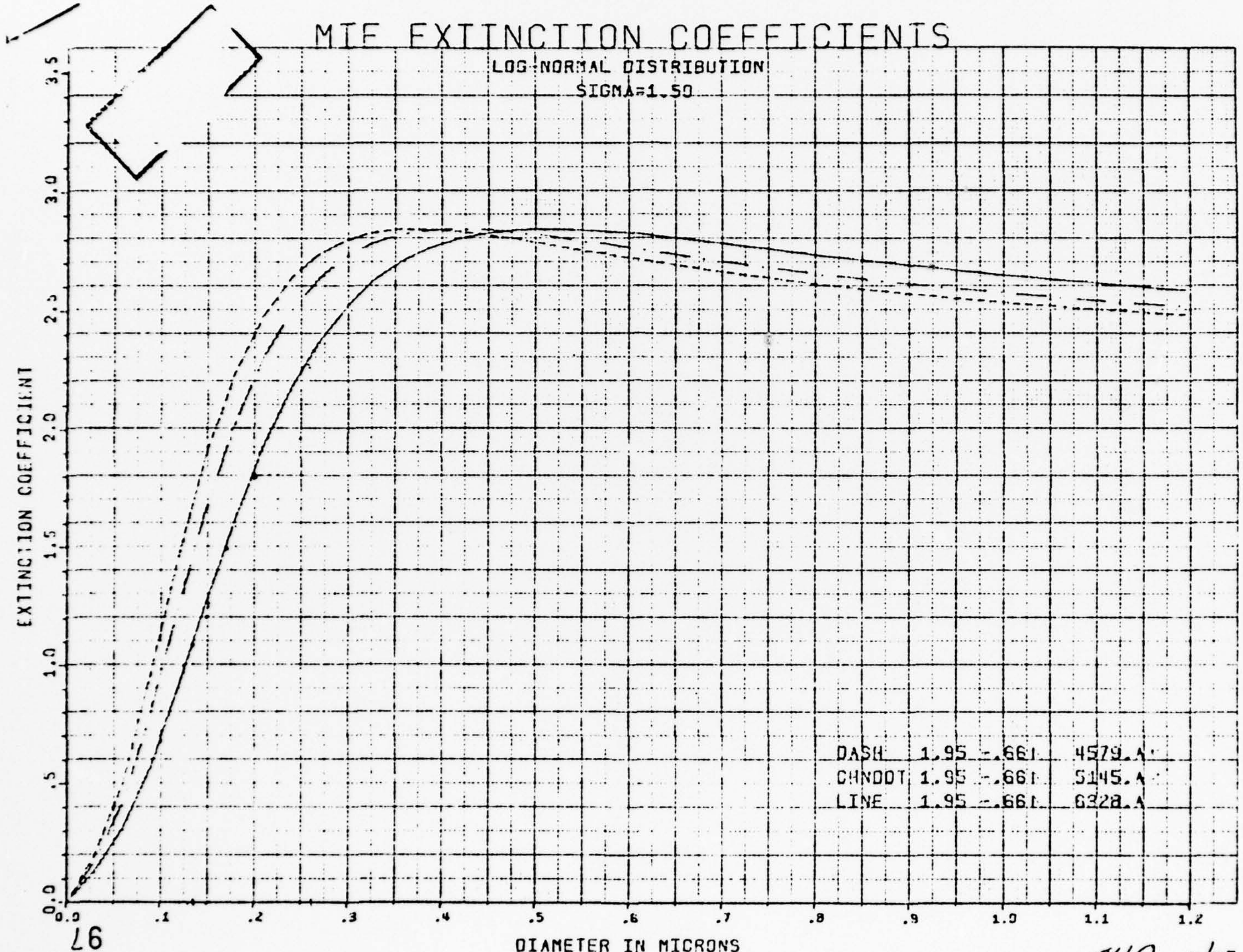

FIGURE 2. EXTINCTION COEFFICIENTS - LOG NORMAL

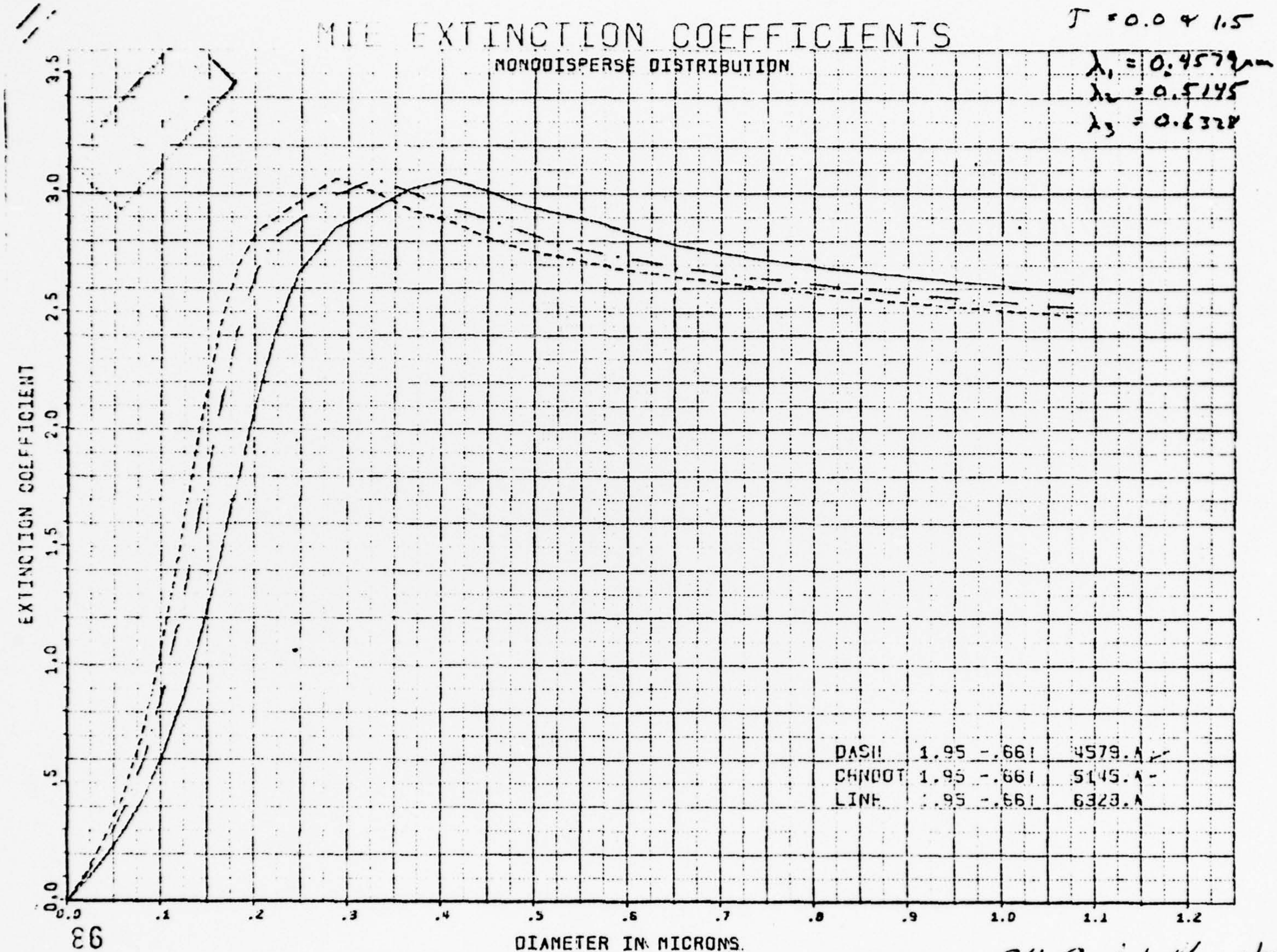

FIGURE 3. EXTINCTION COEFFICIENTS - MONODISPERSED

K.L. Cashdollar 11/77

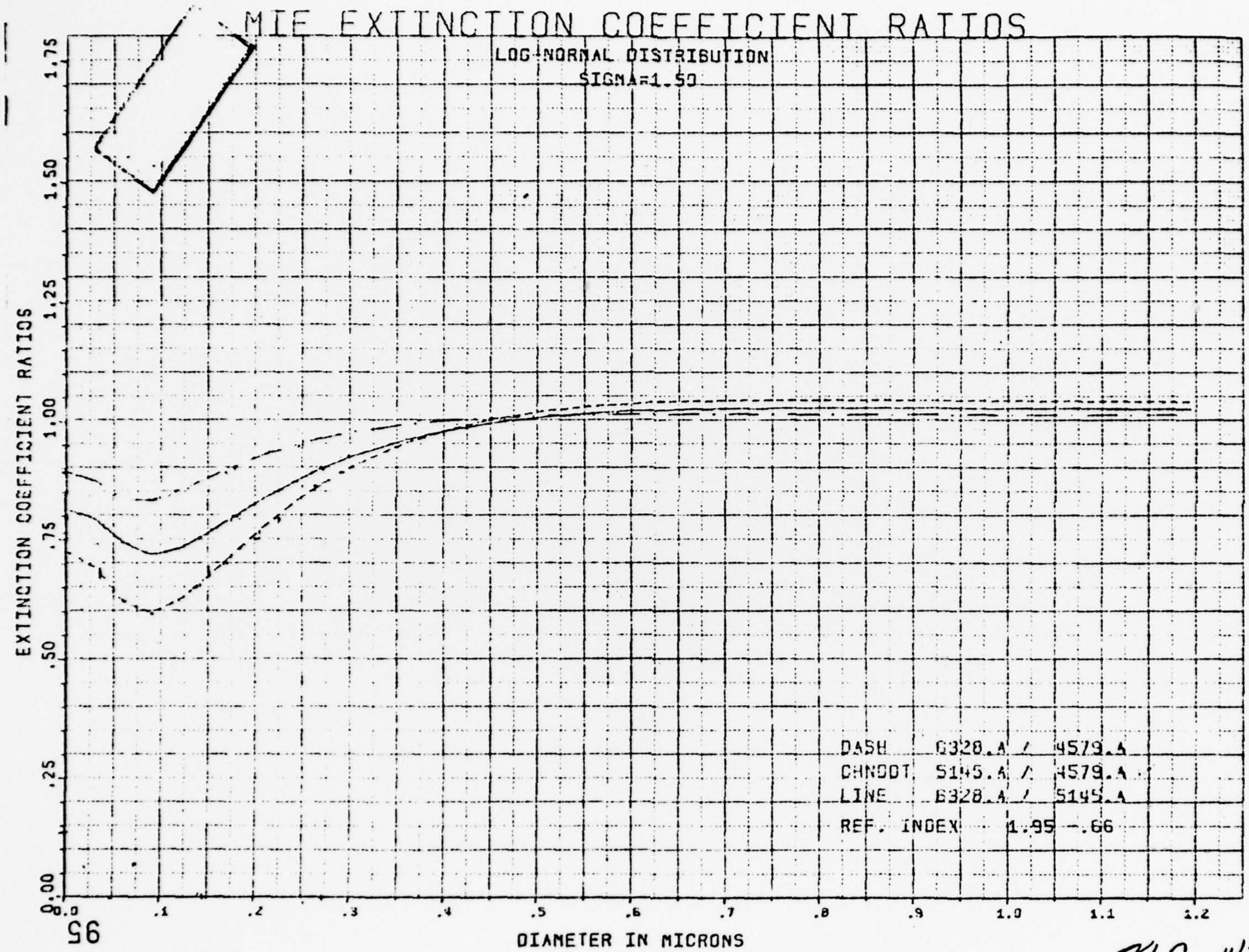

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FIGURE 4. EXTINCTION COEFFICIENT RATIOS - LOG NORMAL

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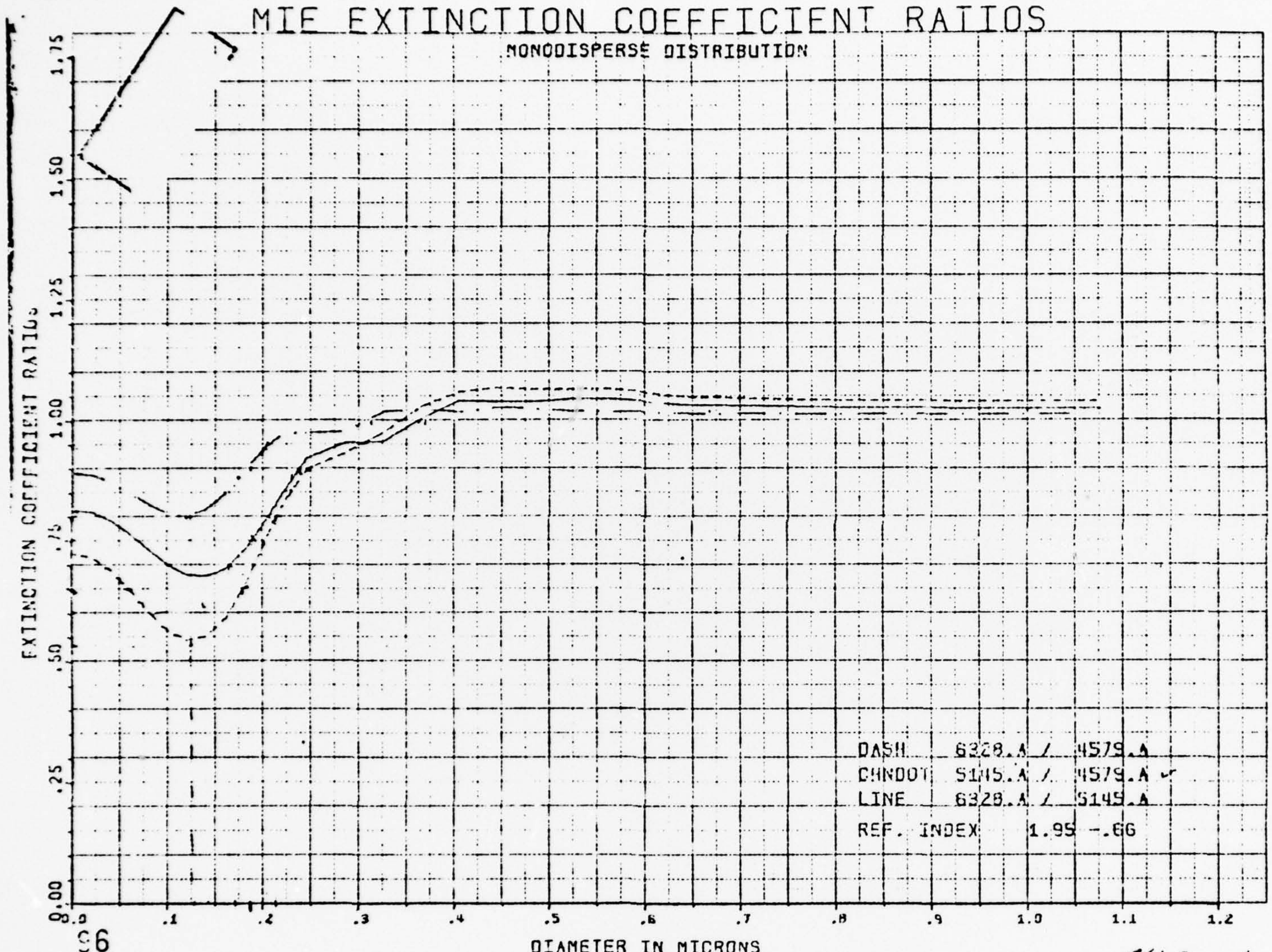

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FIGURE 5. EXTINCTION COEFFICIENT RATIOS - MONODISPERSED

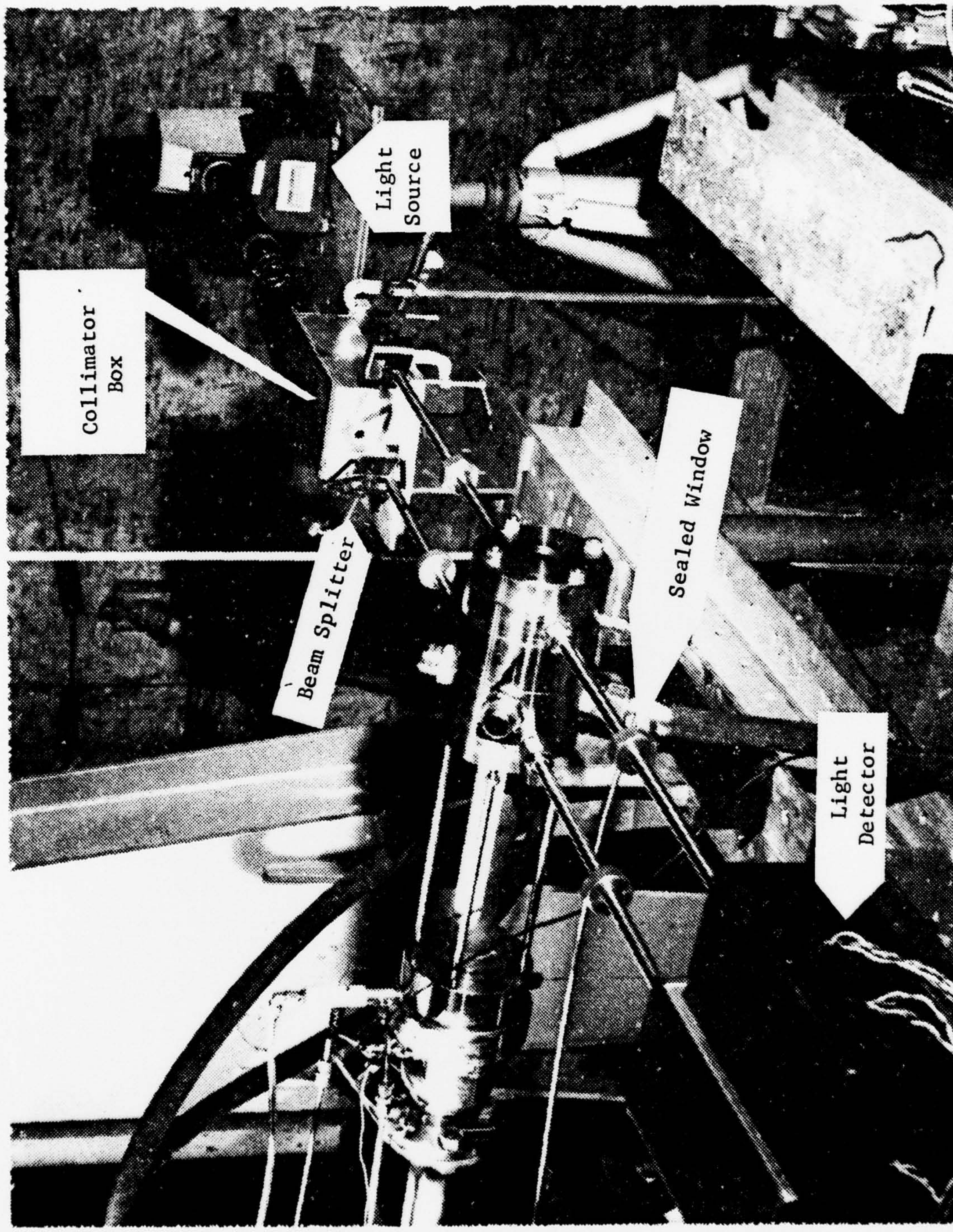

FIGURE 6. TRANSMISSOMETER APPARATUS

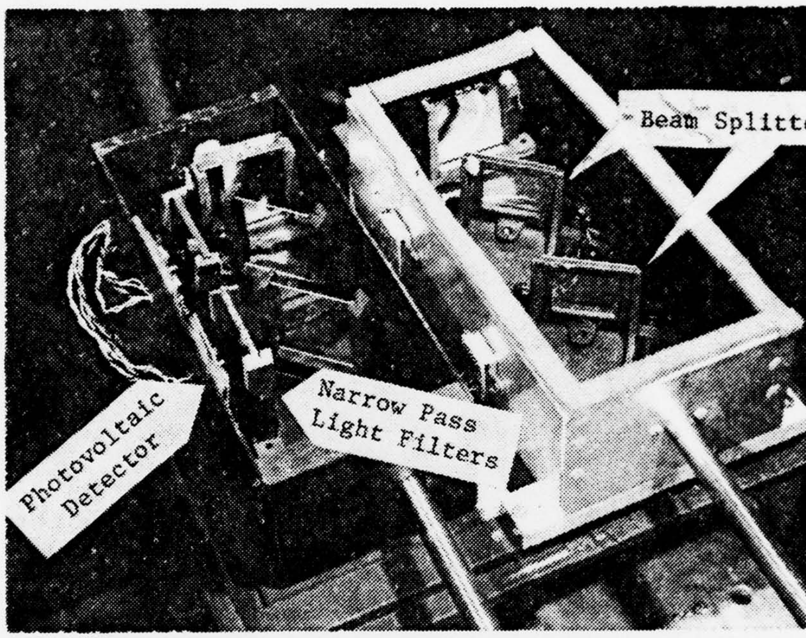

FIGURE 7. LIGHT DETECTOR BOXES

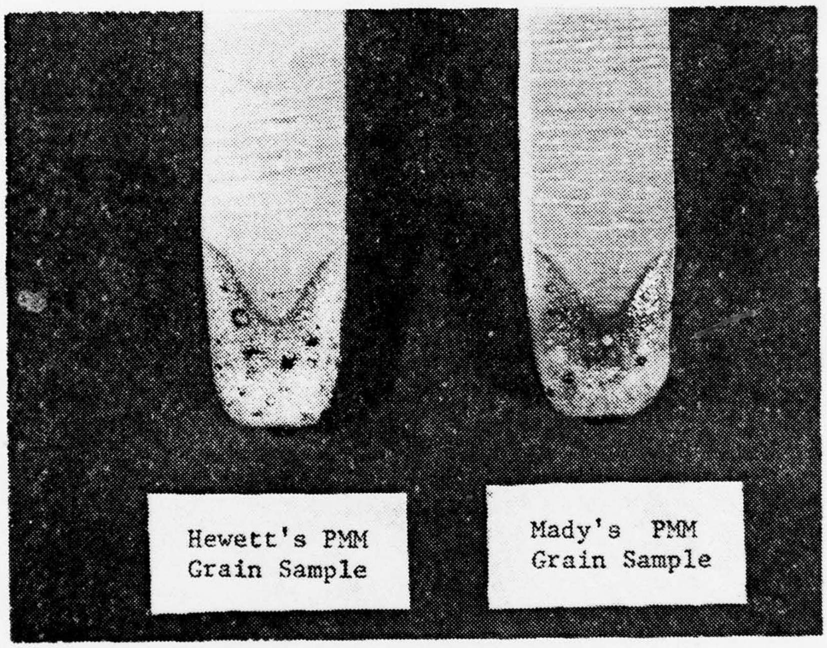

FIGURE 8. PMM ATMOSPHERIC COMBUSTION SAMPLES

APPENDIX A

	PMM												ALL HYDROCARBON	
% BYPASS	100%/0%			70%/30%				50%/50%			30%/70%		100%/0%	50%/50%
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
P_C	54.6	35.6	39.0	54.4	55.9	48.0	58.9	47.4	47.4	47.4	48.8	46.6	49.6	62.1
$\dot{r} \times 10^{-3}$	5.89	4.26	4.24	5.87	6.23	4.67	5.03	4.20	4.10	4.17	4.30	2.95	17.1	14.0
$\dot{\omega}_P$	.203	.123	.145	.199	.203	.14	.128	.107	.102	.106	.100	.07	.297	.20
$\dot{\omega}_S$	0	0	0	0	0	.06	.131	.100	.103	.103	.101	.13	0	.18
A/F_T	12.2	10.6	12.4	13.0	11.7	15.6	18.8	18.2	18.3	18.5	17	20.4	8.89	14.1
A/F_G	12.2	10.6	12.4	13.0	11.7	10.9	9.4	9.11	9.15	9.25	8.5	6.12	8.89	7.05
η	.90	.89	.94	.91	.90	.88	.92	.90	.95	.90	.98	.99	.89	.87
T_F (lbsec)	.57	.78	.70	.74	.71	.46	0	0	0	0	0	0	0	.09
T_B (lbsec)	.94	.87	.97	.79	.78	.71	.65	.66	.59	-	.56	.62	0	.33
D_{32} F μm	.20	.18	.15	.2	.17	.15	-	-	-	-	-	-	-	.125
D_{32} B μm	.14	.45	-	.17	-	.27	.265	.22	.23	-	.30	.17	-	.10
C_m F gm/cm^3	1.67 x10-6	7.48 x10-7	1.14 x10-6	8.9 x10-7	1.04 x10-6	2.49 x10-6	-	-	-	LIGHT SOURCE FAILURE				8.05 x10-6
C_m B gm/cm^3	2.76 x10-7	5.99 x10-7	9.8 x10-8	7.15 x10-7	7.53 x10-7	1.04 x10-6	1.27 x10-6	1.22 x10-6	1.56 x10-6		1.86 x10-6	1.45 x10-6		4.2 x10-6
% FRONT	4.7	3.2	4.9	2.5	2.80	8.5	-	-	-		-	-	-	18.8
% BACK	0.7	2.6	.4	2.0	2.06	3.5	3.9	4.5	6		7.0	6.2	-	10.0

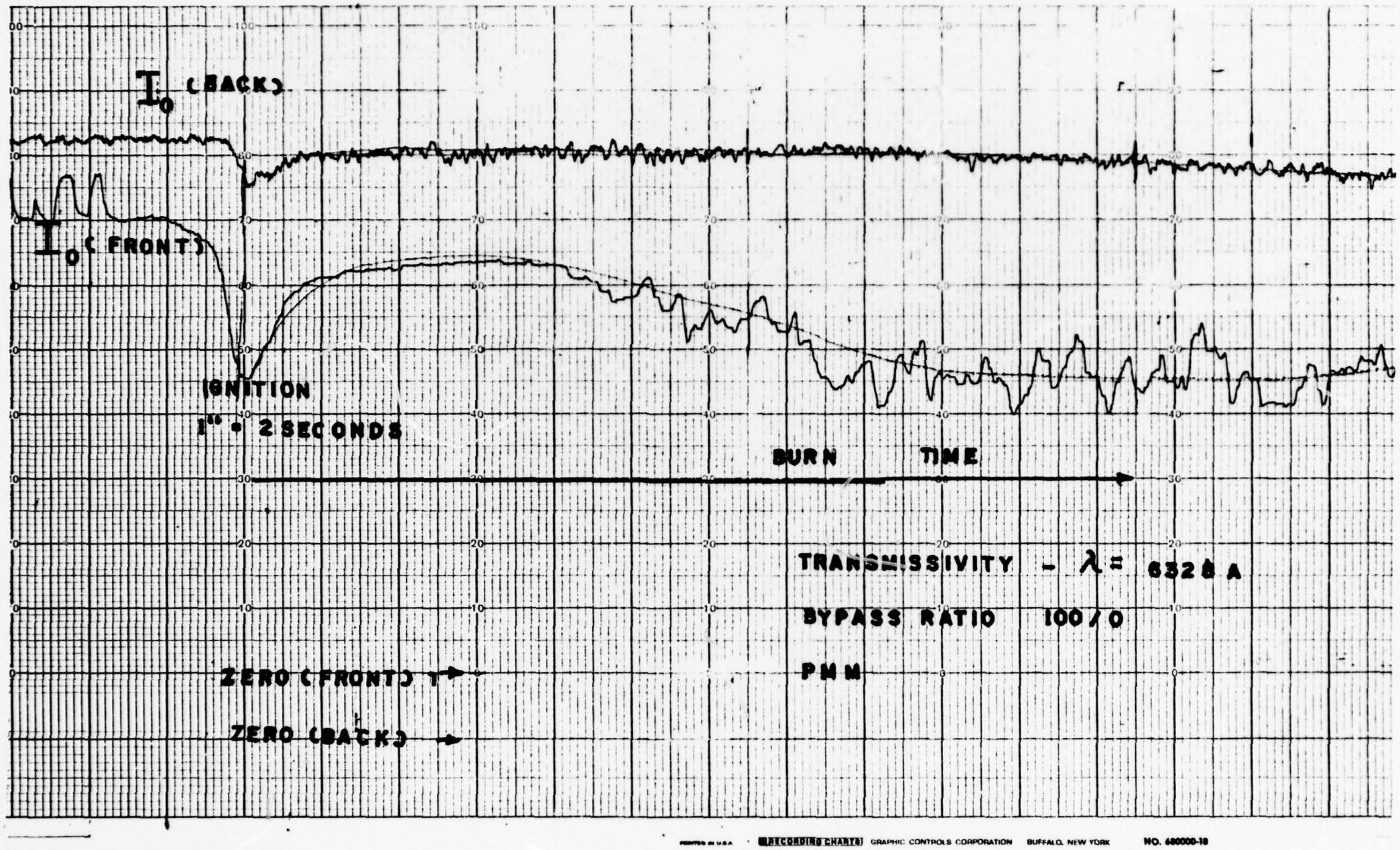

FIGURE 9. SAMPLE LIGHT TRANSMISSION DATA - 100/0

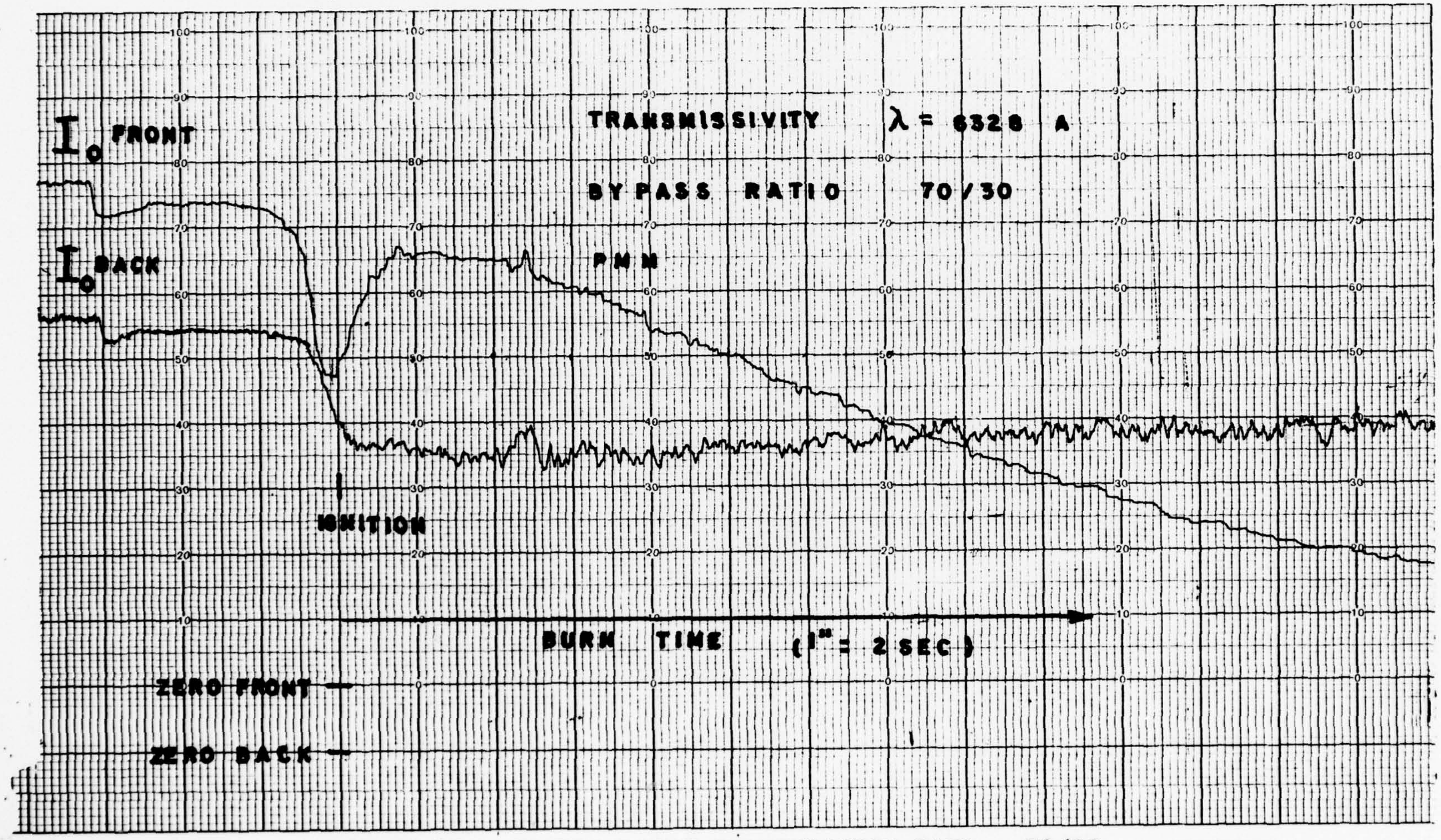

FIGURE 10. SAMPLE LIGHT TRANSMISSION DATA - 70/30

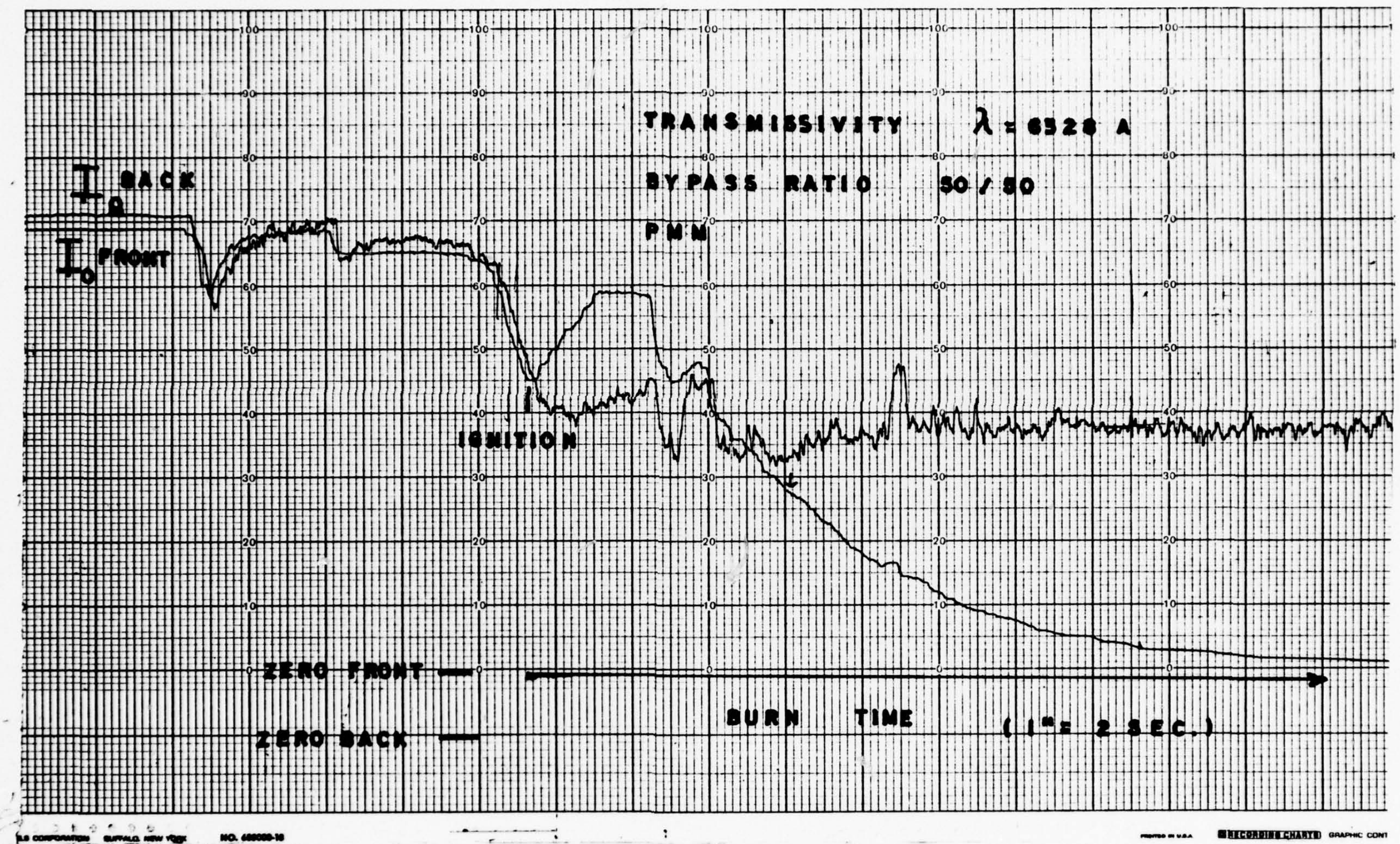

FIGURE 11. SAMPLE LIGHT TRANSMISSION DATA - 50/50

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